Exploration EVA Purge Flow Assessment

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An advanced future spacesuit will require properly sized suit and helmet purge flow rates in order to sustain a crew member with a failed Portable Life Support System (PLSS) during an Extravehicular Activity (EVA). A computational fluid dynamics evaluation was performed to estimate the helmet purge flow rate required to washout carbon dioxide and to prevent the condensing ("fogging") of water vapor on the helmet visor. An additional investigation predicted the suit purge flow rate required to provide sufficient convective cooling to keep the crew member comfortable. This paper summarizes the results of these evaluations.

Nomenclature

EVA	=	Extravehicular Activity
PLSS	=	Portable Life Support System
TD	=	Thermal Desktop®
METMAN	=	41-Node Transient Metabolic Man Program
TTL	=	Time-to-Limit
CO_2	=	Carbon Dioxide
EMU	=	Extravehicular Mobility Unit
CFD	=	Computational Fluid Dynamics
CDO	=	Cognitive Deficit Onset
LCVG	=	Liquid Cooling and Ventilation Garment

I. Introduction

Portable Life Support System (PLSS) purge modes (helmet and suit) are required in the event the suit experiences a failure that disrupts the supply of oxygen to the crew member during an Extravehicular Activity (EVA). During purge mode a valve at the helmet or on the suit is opened, and oxygen is vented out of the suit and into the surrounding vacuum environment. The oxygen that is vented from the suit is supplied by the oxygen tanks in the PLSS suit. This process supplies oxygen to the spacesuit and helmet, which provides the crew member with the required oxygen for breathing, carbon dioxide washout, and convective cooling.

Sizing of the helmet purge flow rate requires an assessment of the impacts on CO_2 washout, with some secondary consideration given to accumulation of metabolic produced water on the inner surface of the helmet bubble (also referred to as 'helmet fogging' in this paper). An assessment of the ability to cool a crewmember with only the convective cooling from the flow of oxygen caused by the purging of the suit is required for the sizing of the suit purge flow rate. These purge flow rates were determined with models developed in Thermal Desktop® and ANSYS® Fluent. This paper summarizes the results from three analyses that looked at CO_2 washout, helmet fogging, and crew member convective cooling performance that resulted from their respective purge mode activity.

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II. Carbon Dioxide Washout Analysis for Helmet Purge Sizing

An analysis was performed to determine the amount of helmet purge flow that would result in the maximum allowable amount of inhaled CO_2 (20 mmHg) [1] by the simulated crew member during a helmet purge activity. The analysis was performed with the Mark III spacesuit CFD model that was used in a previous analysis,[2] with some updates made for this analysis. The model was analyzed for different metabolic rates and helmet purge flow rates.

A. Carbon Dioxide Washout Modeling Assumptions

All of the purge simulations assumed the suit was pressurized to 3.5 psia. Figure 1shows the model that was used for the analysis. The suit geometry was created from a laser scan of a prototype suit. The model extends down to about the waist area of the suit. The location of the helmet purge valve duct opening was assumed to be in the neck ring portion of the suit (Figure 2). This purge valve opening was added (original model [2] did not include it) in order to assess helmet purge activities. The size of the purge valve duct was assumed to be 3 in. by 0.5 in. The purge valve opening was given an exit velocity boundary condition based on the assumed purge volumetric flow rate and the area of the duct.

Another update that was added to the CFD model was the inlet air duct (Figure 3). The air duct was not only designed to provide ventilation, but to also direct the gas flow along the inner surface of the helmet bubble. This was done in order to maximize the CO_2 washout effectiveness and to minimize helmet fogging. The air duct was assumed to provide the suit with 50°F oxygen (100% concentration) during the purge activity. The ventilation air duct was assumed to be 6.5 inch by 0.25 inch at its outlet location (labeled "Air Duct Helmet Inlet" in Figure 3). Note that this inlet duct geometry has not previously been built or tested but is recommended for future CO_2 washout testing.

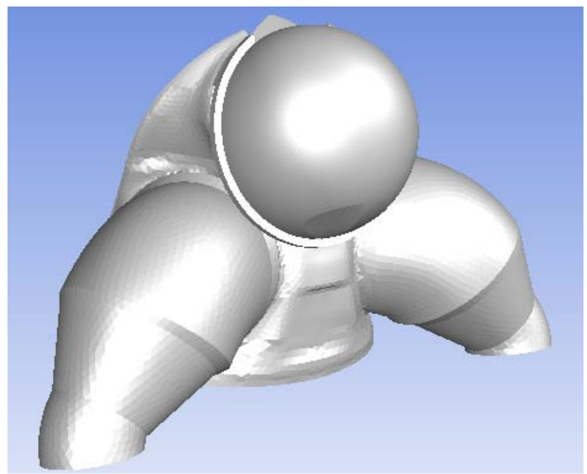


Figure 1. Mark III Suit Model

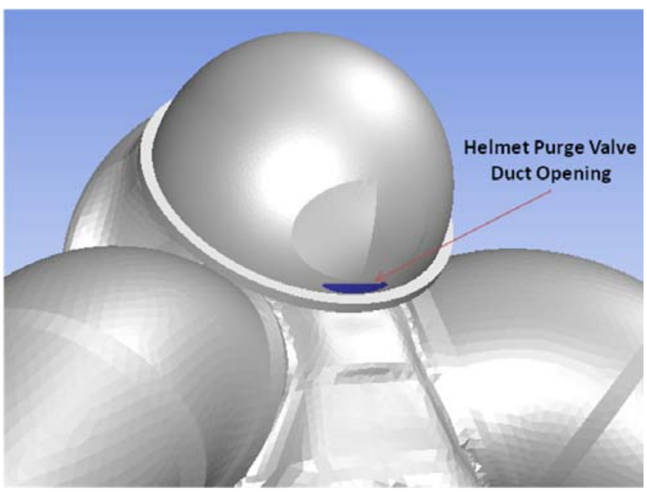


Figure 2. Helmet Purge Valve Duct Opening

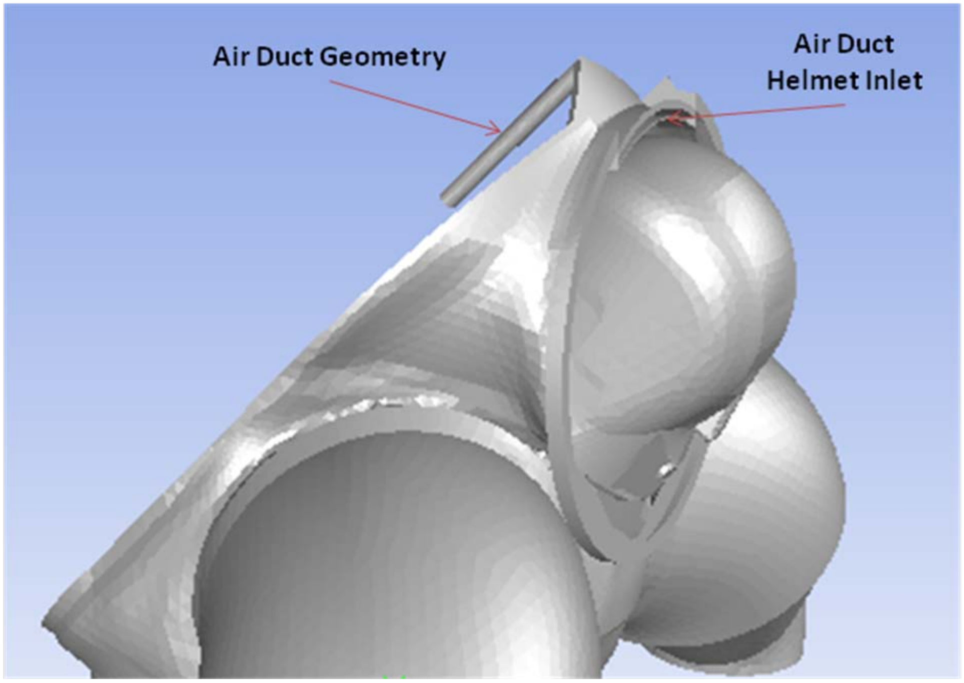


Figure 3. Air Duct Geometry (helmet bubble not shown)

The simulated human was assumed to have a 5.5 second breathing cycle (2.25 sec inhale/3.25 sec exhale), which was based on data from the Bioastronautics Data Book [3] and shown in Figure 4. The curve labeled "14 cm H_2O/liter, sec" was chosen and curve fitted for the analysis. The breathing cycle was modeled with velocity boundary conditions at the mouth and nose of the simulated human (Figure 5). The temperature of the air being exhaled by the simulated human was assumed to be at 98°F. The original model was updated with user logic that determined the amount of each species (H_2O (vapor), O_2, and CO_2) inhaled, and then calculated and set the mass fraction of each species that would be exhaled at the boundary. The water vapor exhaled from the mouth and nose of the simulated crew member was set to a mass fraction that would yield a fully saturated condition (100% relative humidity) for an assumed temperature of 98°F. The rate of oxygen removed during the inhale portion was calculated with the equation 1,[4] and the CO_2 production rate was calculated with equation 2.

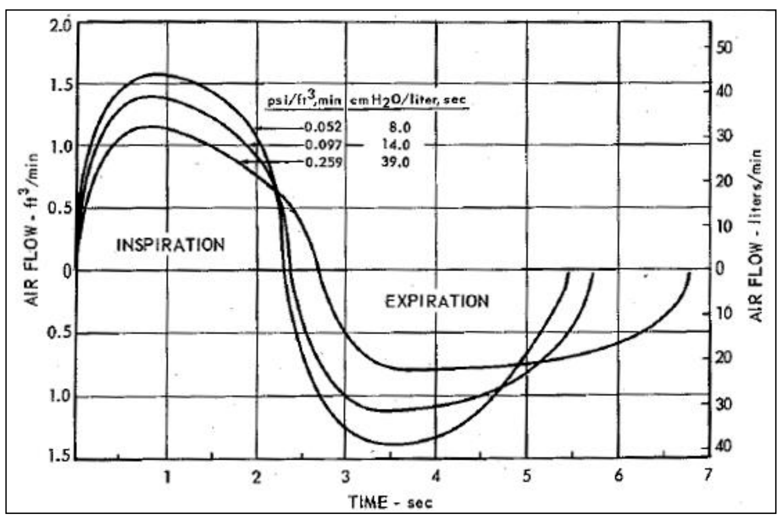


Figure 4. Human Breathing Cycle

(1)

(2)

Where, is the computed oxygen consumption rate (lbm/hr), is the computed carbon dioxide rate (lbm/hr), is the assumed metabolic rate (BTU/hr), and is the assumed respiratory quotient. Metabolic rates equal to 800 BTU/hr, 1600 BTU/hr, and 2000 BTU/hr were analyzed with the CFD model, and all cases assumed a respiratory quotient equal to 0.9. The required helmet purge flow rate to meet the maximum allowable inhale CO2 value of 20 mmHg for each metabolic rate was not known a priori. Therefore, an iterative process was performed to determine the ventilation flow rates.

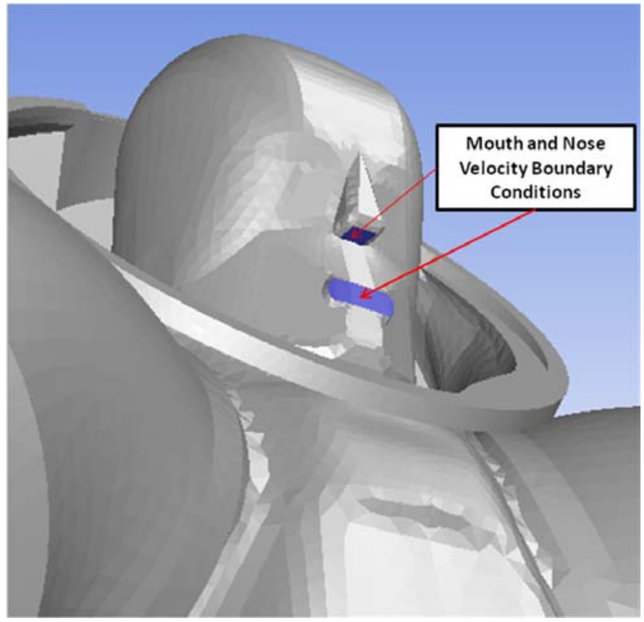


Figure 5. Simulated Human Breathing Boundary Conditions

B. Carbon Dioxide Washout Results

The helmet purge flow rates that gave an inhaled CO_2 value of 20 mmHg for the different metabolic rates were documented in Table 1. The analysis showed that higher ventilation flow rates were required for higher metabolic rates, which was expected because larger metabolic rates produce higher amounts of CO_2.

Table 1. Carbon Dioxide Washout Ventilation Flow Rates

	CO_2 Washout Helmet Purge Flow Rates		
Metabolic Rate (BTU/hr)	2000	1600	1200
Predicted Flow Rate (actual cubic feet per minute) that gave a CO_2 inhale value of 20 mmHg	1.7	1.5	1.2

Figure 6 shows the oxygen entering the suit (from the air duct) and being directed along the inner surface of the helmet bubble, which was the intended result of the air duct design. The pathlines were colored by CO_2 mole fraction. The data in the figure shows the flow coming into the helmet at a low CO_2 concentration (zero, dark blue color), and then increasing in CO_2 concentration in front of the modeled crew member. The "paths" shown assume steady-state conditions based on a time point toward the end of the exhale part of the breath cycle. The actual flow field in the model simulation was transient in nature, therefore the actual "paths" are moving with respect to time. However, the pathlines in the figures captured the generic behavior of the flow and were used to illustrate that behavior. CFD results from the CO_2 washout effort were used to assess helmet bubble fogging concerns during helmet purge activities, which will be discussed in the next section.

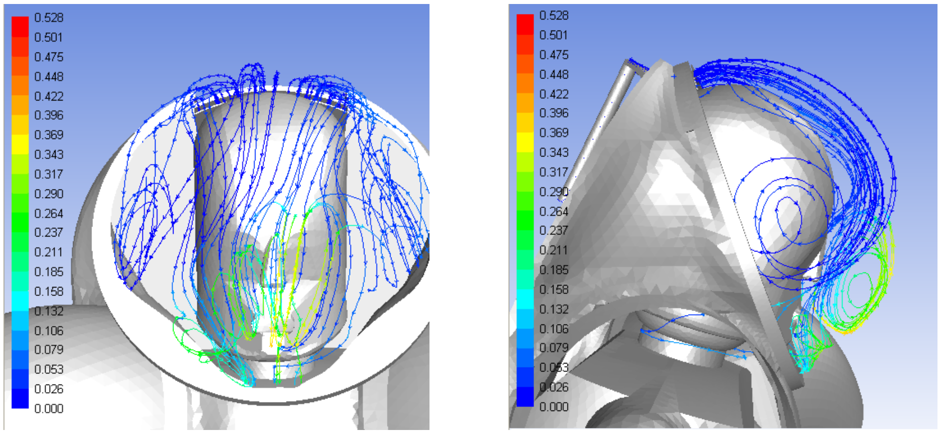


Figure 6. CO2 Mole Fraction Pathlines from Air Duct

III. Helmet Bubble Fogging During Helmet Purge

An analysis was performed to determine the amount of helmet fogging (if any) during a helmet purge operation for CO_2 washout. If fogging did occur, the required helmet purge flow rate to prevent fogging was assessed. The analysis was performed with the results of the CO_2 washout CFD analysis and a visor spreadsheet thermal model that was based on a helmet SINFLO model.[5]

C. Helmet Fogging Modeling Assumptions

The analysis assumed the suit helmet was composed of a pressure bubble and a protective visor (Figure 7, taken from Ref. 5). The visor spreadsheet model was used to calculate the temperature of the inside surface of the pressure bubble (labeled 2 in Figure 7). The inner bubble temperature was then compared to the dew point temperature of the air inside the bubble (computed with CFD model) to determine if helmet fogging would occur. The visor spreadsheet model assumed that the only mode for heat transfer was by radiation, with convective heat transfer between the air in the helmet and the pressure bubble wall being ignored.

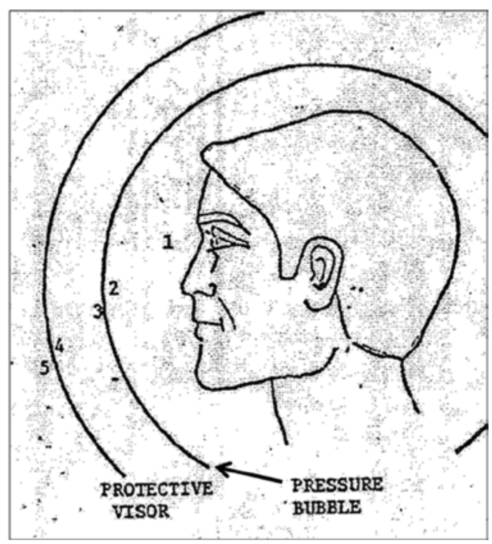


Figure 7. Protective Visor and Pressure Bubble

The model only looked at extreme cold environments because those are the driving conditions that could produce the largest amount of helmet fogging. The model assumed the crew member was facing a sink temperature environment equal to -325°F, representative of a shadowed moon crater at the poles. The visor spreadsheet model predicted an inner pressure bubble temperature equal to 53°F for this worst case cold thermal environment. A sink temperature equal to absolute zero was also looked at, but little variation was observed for the calculated inner bubble temperature when compared to the -325°F sink temperature. Survey of the literature showed that there is a requirement to keep the gas in the helmet at a dew point temperature no greater than 64°F.[6] This translates into keeping the pressure bubble inner temperature at or above 64°F to prevent fogging at that dew point temperature. Therefore, in addition to the worst case inner bubble temperature of 53°, an inner bubble temperature of 64°F was also assessed.

Assumed air temperatures of 53°F and 64°F at the helmet bubble inner wall gave water saturation pressures equal to 0.2 psia and 0.296 psia, respectively. Therefore, CFD predicted water vapor partial pressures at the inner surface of the pressure bubble greater than 0.2 psia or 0.296 psia were assumed to produce fogging. The air being

exhaled by the simulated crew member was assumed to be fully saturated with water vapor, regardless of the assumed metabolic rate. With that modeling assumption, the helmet fogging analysis was able to leverage all of the CFD cases used for the CO_2 washout analysis without a need to distinguish the cases based on metabolic rate.

In addition to the 100% water vapor saturation assumption for exhaled gases, the amount of water vapor produced by the simulated crew member was also a function of the volumetric breathing pattern (Figure 4). The volumetric breathing pattern assumed for all of the CFD cases, plus the saturated exhale gas assumption, yielded respiratory water production rates representative of a low metabolic rate (~750 BTU/hr). This was done to assess if fogging would occur for water vapor production rates created under low metabolic rates conditions (i.e. breathing pattern). This assumption did not impact the CO_2 washout analysis because the model compensated the breathing pattern with higher CO_2 mass fractions, which overall yielded the proper CO_2 production rates.

D. Helmet Fogging Results

The water saturation pressures equal to 0.2 psia and 0.296 psia were converted into mole fractions in order to use the CFD post-process tools and results from the CO_2 washout analysis. The 0.2 psia and 0.296 psia saturation pressures gave mole fractions equal to 0.0571 and 0.0845, respectively, based on the 3.5 psia total suit pressure. These mole fractions were then used as lower limit mole fractions for helmet water vapor contour plots. Water vapor mole fraction contours for an assumed flow rate of 1.7 acfm are shown in Figure 8. The data used for the contour was taken towards the end of the exhale breath, which produced the highest level of water vapor on the inner surface of the helmet bubble.

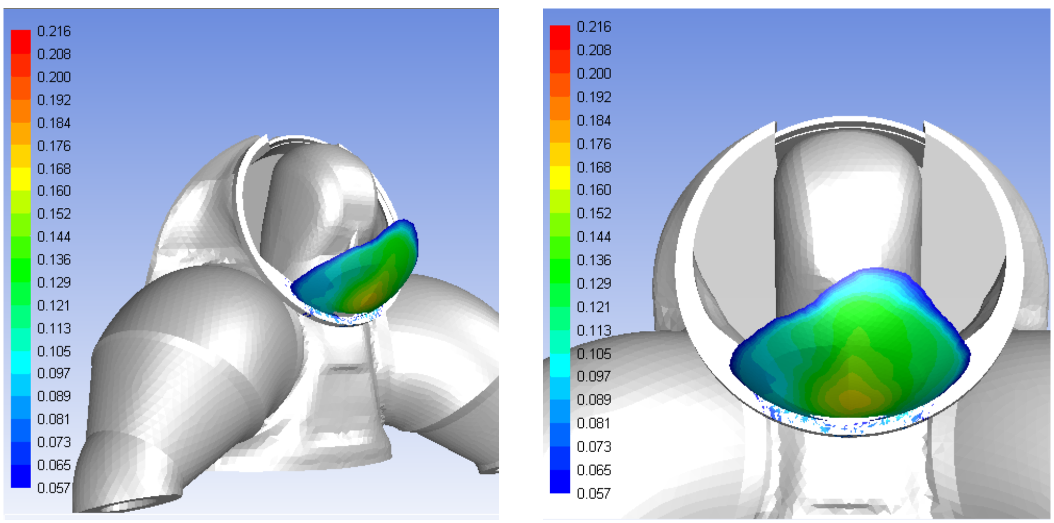


Figure 8. Water Vapor Mole Fraction Contours for a 1.7 actual cubic feet per minute helmet purge flow rate

For a helmet purge flow rate of 1.7 acfm, the model predicted water vapor mole fractions ranging from 0.057 to 0.216 on portions of the helmet bubble (see Figure 8). These mole fractions translated into water vapor partial pressures ranging from 0.2 psia (saturation pressure for 53°F) to 0.756 psia (saturation pressure for 92.5°F). Locations on the helmet bubble populated with contour data are areas where fogging was predicted to occur. Examination of the contours in Figure 8 showed that the amount of fogging would degrade the crew member's field of view. Increasing the saturation pressure to 0.296 psia (64°F helmet assumed bubble temperature) made little change to the amount of fogging on the helmet bubble surface.

Water vapor mole fraction contours for a helmet purge rate of 1.2 acfm, the lowest analyzed for the CO_2 washout analysis, are shown in Figure 9. The mole fraction contours corresponded to water vapor partial pressures that ranged from 0.2 psia to 0.756 psia. The amount of fogging (contour area) predicted for this case was larger than that predicted for the 1.7 acfm helmet purge flow rate.

An additional CFD case was performed with an assumed helmet purge flow rate equal to 4 acfm in order to determine the amount of fogging reduction. Water vapor mole fraction contours for this case are shown in Figure 10. The data showed a reduction in the amount of fogging (contour area) predicted on the inner wall of the helmet bubble for an assumed water vapor saturation pressure of 0.2 psia (saturation pressure for 53°F). The model still predicted that fogging would occur on a portion of the helmet bubble, but the location and size of the fogging area caused less degradation to the crew member's field of view when compared to the lower flow rate cases.

The maximum water vapor partial pressure at the surface of the helmet bubble was taken from all the CFD cases analyzed and plotted in Figure 11. Two horizontal lines were added to the plot to highlight the saturation pressures at 0.2 psia (red line) for 53°F and 0.3 psia (orange line) for 64°F. The maximum water vapor partial pressures at the helmet bubble would have to be below 0.3 psia or 0.2 psia in order to prevent fogging on the innler surface of the helmet bubble at a temperature of 64°F or 53°F, respectively.

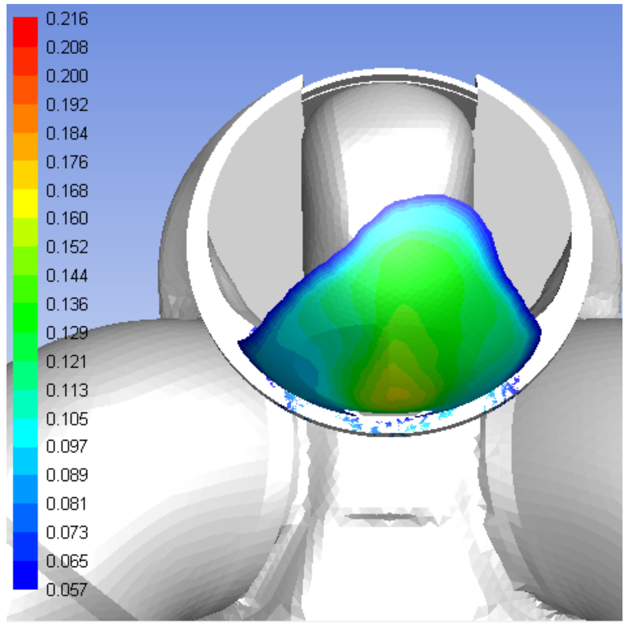


Figure 9. Water Vapor Mole Fraction Contours for a 1.2 actual cubic feet per minute helmet purge flow rate

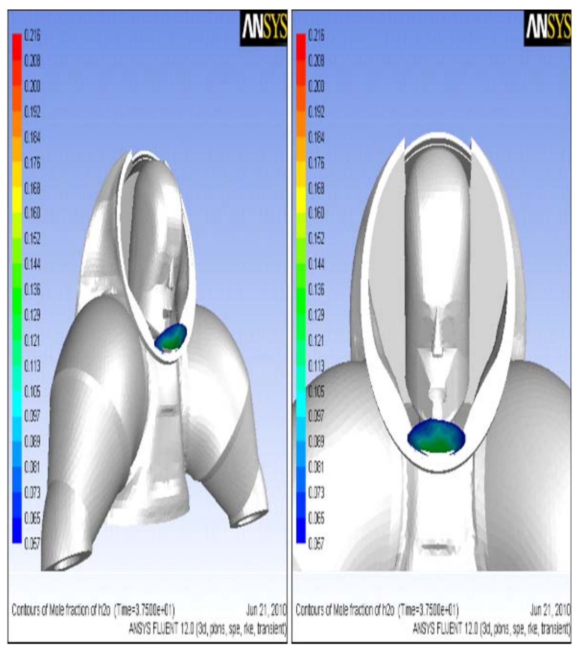


Figure 10. Water Vapor Mole Fraction Contours for 4 actual cubic feet per minute helmet purge flow rate

A linear regression of the data predicted the helmet flow rate would have to be 7 acfm and 9 acfm in order to prevent fogging on the inner surface of the helmet bubble at a temperature of 64°F and 53°F, respectively. These higher flow rates would result in a penalty on the sizing of the oxygen tank in order to deliver these flow rates. In addition, as previously mentioned, the breathing pattern assumed for all the CFD cases was representative of a low metabolic rate (~750 BTU/hr) in terms of respiratory water production. Therefore, the amount of water vapor produced was for best case fogging conditions. Adjusting the breathing pattern for higher metabolic rates would result in higher levels of fogging on the helmet bubble, which in turn would require larger helmet purge flow rates to prevent fogging. The results from the relatively low metabolic rate cases analyzed yield impracticle high purge flow rates and higher metabolic rate conditions were therefore not analyzed. An alternative approach to prevent fogging might be to coat the inner surface of the helmet bubble with an anti-fogging material if this approach is successful.

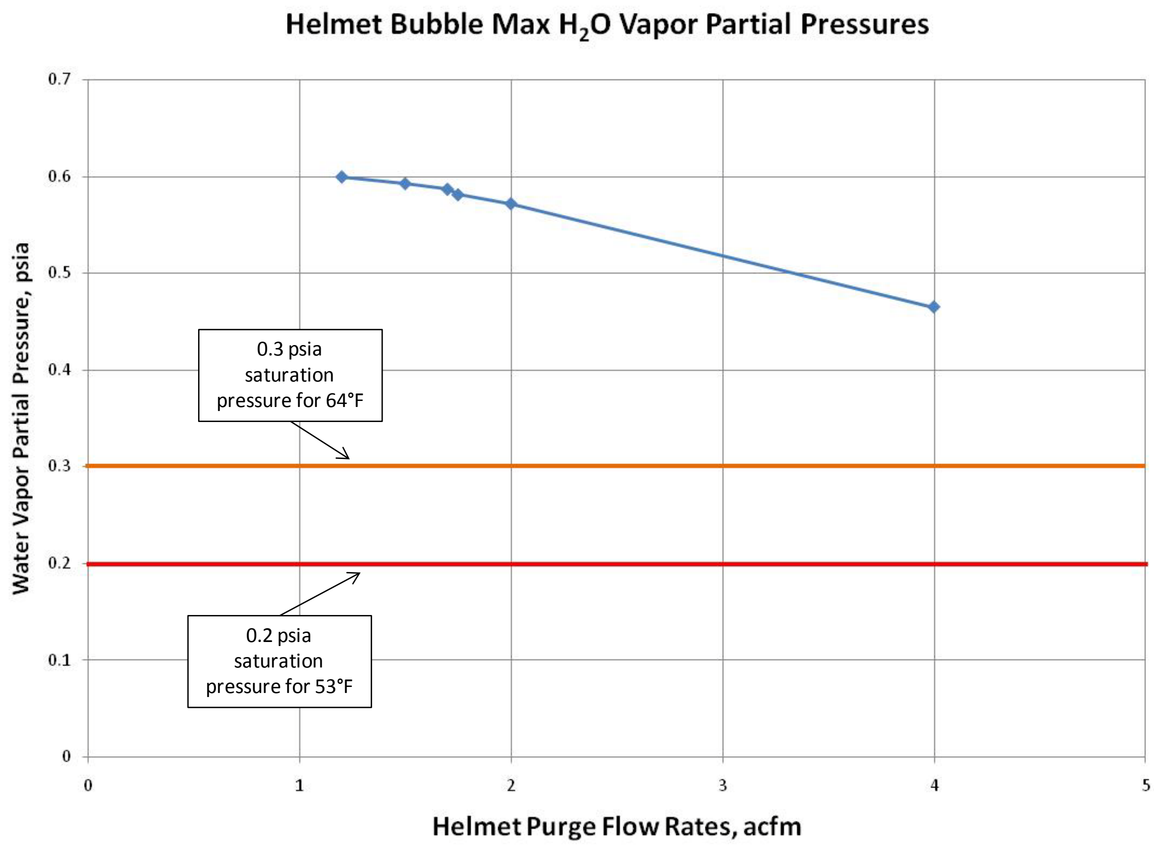


Figure 11. Helmet Bubble Max Water Vapor Partial Pressures

IV. Ventilation Cooling Analysis for Suit Purge Analysis

An analysis was performed to determine the needed convective cooling for keeping a crew member comfortable during a suit purge activity. The analysis was performed with the PLSS Thermal Desktop® (TD) model with the 41-Node Transient Metabolic Man Program (METMAN) integrated. The model was analyzed with different metabolic rates, external environmental conditions, and suit purge flow rates.

E. Ventilation Cooling Modeling Assumptions

The secondary oxygen purge capability for the next generation space suit is currently required for a minimum duration of 30 minutes.[6] The crewmember heat storage level at which Cognitive Deficit Onset (CDO) occurs is 2.0 BTU/lb,[7] which corresponds to 300 BTU of heat storage for a 150 lb crewmember. In order to keep the crew member comfortable, the ventilation cooling requirement assumed in this evaluation was to maintain heat storage below 300 BTU for 30 minutes. Future references in this document to the time required for the simulated crew member to reach a heat storage value of 300 BTUs will be referred to as the time-to-limit (TTL). All of the cases allowed the simulated crew member to reach steady-state conditions under an assumed functional PLSS (working liquid cooling loop) prior to the suit purge ventilation cooling transient. This modeling assumption was done for two reasons. The first reason was that a suit purge operation was assumed to be a response to an unplanned failure, and it was assumed that the crew member was being kept comfortable prior to the suit purge. The second reason was that it was desired to accurately calculate the time it took the heat storage of the simulated crew member to go from zero to 300 BTUs.

All of the cases assumed the suit was operating at an absolute pressure of 3.5 psia. The gas supplied to the helmet was assumed to be composed of 100% oxygen and at a temperature of 50°F. A few cases were analyzed with

the incoming oxygen set at 20°F, but little difference was observed in the calculated TTLs when compared to the 50°F cases. All of the cases were simulated for maximum run-time of 120 minutes, regardless if the simulated crew member reached a heat storage value of 300 BTU or not.

The analysis cases looked at 4 metabolic rates, 5 ventilation flow rates, and 3 external thermal environments, which all together amounted to a total of 60 cases. The 4 metabolic rates assessed were 800 BTU/hr (low activity), 1200 BTU/hr (moderate activity), 1600 BTU/hr (moderate activity), and 2000 BTU/hr (high activity). Suite purge flow rates equal to 2 acfm, 3 acfm, 4 acfm, 6 acfm, and 12 acfm were analyzed. The flow rates equal to 2 acfm, 3 acfm, and 4 acfm were representative of realistic suit purge flow rates. The purge flow rate equal to 6 acfm was representative of a flow rate typically driven by a fan (ex. Shuttle Extravehicular Mobility Unit (EMU)), and was chosen in order to quantify the additional amount of cooling possible with slightly larger purge flow rates. Although the 12 acfm flow rate was considered an unrealistic flow rate for a suit purge activity, it was analyzed in order to fully understand and to quantify the benefits and limitations of high suit purge flow rates. In addition, a survey of available literature showed that the Skylab EMU operated at ventilation flow rates as high as 10.8 acfm,[8] making 12 acfm a legitimate upper ventilation flow rate limit.

The different external thermal environments were modeled as sink temperatures. Sink temperatures equal to -325°F (cold), 70°F (moderate), and 250°F (hot) were analyzed. A sink temperature of -325°F is considered to be representative of being at locations on the moon with no sunlight (ex. lunar poles, craters, etc.). A sink temperature of 250°F is considered representative of being inside a crater at the moon's sub-solar point.

F. Ventilation Cooling Results

TTL results for all of the 60 cases are shown in Table 1. The table shows the TTLs (in minutes) for different external thermal environments, volumetric flow rates, and metabolic rates. Values displayed as "120*" indicate a heat storage value of 300 BTU's was not reached within the 120 minute (2 hour) simulation. The general trend in the data showed that the TTL was maximized during high flow rates, low metabolic rates, and at the cold thermal environment. In contrast, the TTL was minimized during low flow rates, high metabolic rates, and at the hot thermal environment.

Table 2. Times to Reach 300 BTU Heat Storage

Times to Reach 300 BTU Heat Storage in Minutes															
Metabolic Rate, BTU/hr	Cold Environment, -325°F					Moderate Environment, 70°F					Hot Environment, 250°F				
Volumetric Flow Rate, acfm	2	3	4	6	12	2	3	4	6	12	2	3	4	6	12
800 BTU/hr	48.2	64.2	90.2	120*	120*	41.5	58.2	118.9	120*	120*	27.7	33.1	42.0	120*	120*
1200 BTU/hr	23.6	26.0	28.2	35.9	120*	22.4	24.9	27.9	36.2	120*	18.3	19.9	21.4	25.1	43.6
1600 BTU/hr	15.6	16.8	17.7	19.5	23.3	15.0	16.4	17.4	18.9	21.1	13.2	14.4	15.0	15.9	17.0
2000 BTU/hr	11.5	12.4	12.9	13.7	14.4	11.3	12.1	12.8	13.4	13.8	10.2	11.0	11.6	12.0	12.3

* Cases simulated for only 120 minutes

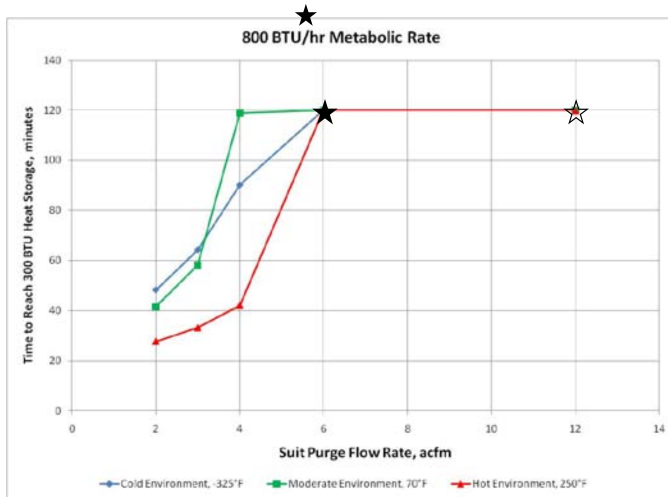
The data from the 60 cases were also plotted in figures, where the metabolic rate was kept constant in each of the figures. The time-dependent data for the 800 BTU/hr, 1200 BTU/hr, 1600 BTU/hr, and 2000 BTU/hr metabolic rate cases are shown in Figures 12, 14, 15 and 16, respectively. The figures showed the same general trend, which is that increasing the suit purge flow rate increased the time it took the simulated crew member to reach a heat storage amount of 300 BTUs. The data showed a larger difference in ventilation cooling performance between the hot and moderate thermal environment than that observed between the moderate and cold thermal environments. Some of the cases did not reach a heat storage value of 300 BTUs during the 120 minute simulation. Those cases were identified with "stars" in the figures.

All of the cases that assumed an 800 BTU/hr metabolic rate showed a minimum TTL of 30 minutes, except for the case that assumed a flow rate of 2 acfm in a hot thermal environment (27.7 min TTL). Purge flow rates equal to 6 and 12 acfm gave the simulated crew member adequate comfort for at least 120 minutes (2 hours). The model predicted that the crew member would be kept comfortable for a longer time period in a moderate thermal environment versus a cold thermal environment for the same 4 acfm flow rate. This result was unexpected, because it was believed that cold thermal environments would always yield longer comfort periods than moderate thermal environments. Further examination of the data showed this to be true for the first 20 minutes of the simulation (see Figure 13). Note that sensible cooling at time zero is high because liquid sensible cooling in the Liquid Cooling and

Ventilation Garment (LCVG) is simulated for preconditioning for each case and is turned off at time zero. However, the total heat removal rate of the crew member in the moderate thermal environment (green dashed line) starts to exceed the heat removal rate of the crew member in the cold thermal environment (green solid line) after the 20 minute mark of the simulation. The total heat removal rate (green dashed line) of the crew member in the moderate thermal environment becomes strongly dominated by latent heat removal (red dashed line). Although the simulated crew member in the cold thermal environment received more sensible cooling (blue solid line vs. blue dashed line), the sensible heat removal contribution was less than the contribution attributed to latent heat removal. The latent heat removal in the moderate thermal environment was higher because the warmer air (compared to cold thermal environment) was able to hold more water vapor.

The moderate and cold thermal environment cases for the 1200 BTU/hr metabolic rate yielded similar TTLs for a given assumed suit purge flow rate. This can be seen in Figure 3, where the moderate thermal environment data (green) is plotted on top of the cold environment data (blue). The simulated crew member could not be kept comfortable for 30 minutes for purge flow rates ranging from 2 to 4 acfm. A TTL greater than 30 minutes was produced for a flow rate equal to 6 acfm under cold and moderate thermal environment conditions. A purge flow rate equal to 12 acfm was required to keep a simulated crew member with a 1200 BTU/hr metabolic rate comfortable for 43.6 minutes at a thermal environment representative of the lunar sub-solar crater environment. For the cases analyzed, the data indicate a crew member could not be kept comfortable by convective cooling means at the lunar sub-solar point (hot thermal environment) during a 30 minute suit purge for flow rates equal to or less than 6 acfm.

For the high metabolic rate cases, 1600 BTU/hr (Figure 4) and 2000 BTU/hr (Figure 5), none of the suit purge flow rates analyzed were able to provide the needed convective cooling for the desired minimal time frame of 30 minutes. At these elevated metabolic rates the TTL ranged from 10 minutes (2000 BTU/hr, hot environment, 2 acfm) to 17.7 minutes (1600 BTU/hr, cold environment, 4 acfm) for suit purge flow rates ranging from 2 to 4 acfm. Increasing the suit purge flow rate



★- Cases were only simulated for 120 minutes

Figure 12. 800 BTU/hr Metabolic Rate Cases

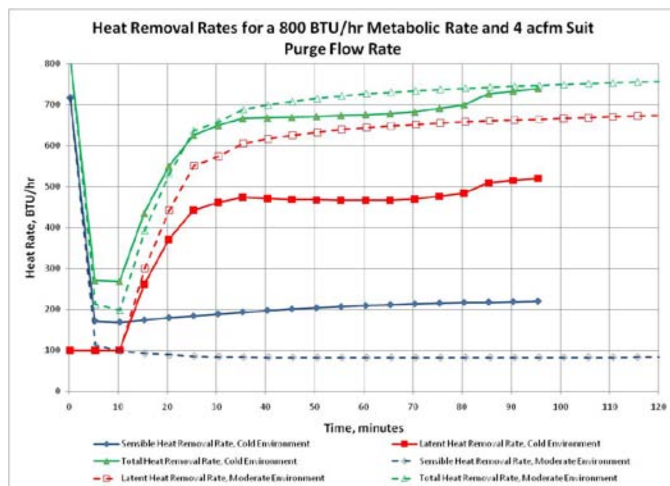
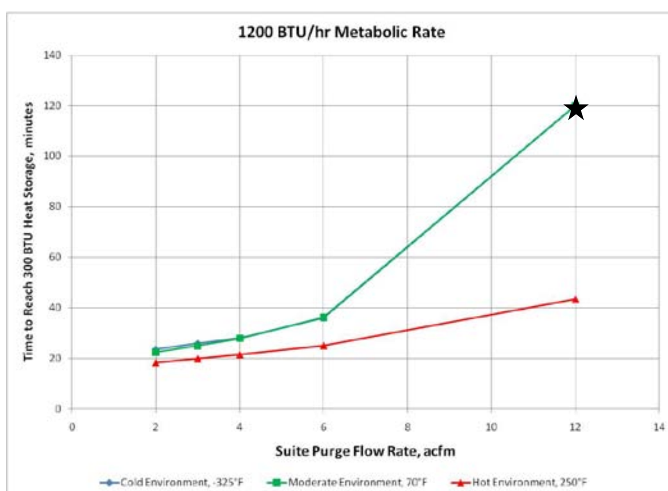


Figure 14. Heat Removal Rates for an 800 BTU/hr Metabolic Rate and 4 acfm Suit Purge Flow Rate



★- Cases were only simulated for 120 minutes

Figure 13. 1200 BTU/hr Metabolic Rate Cases

to 6 and 12 acfm gave only a few extra minutes of additional cooling. The results for the cases analyzed show that a suited crew member at high metabolic rates could not be cooled for a 30 minute period with only convective cooling.

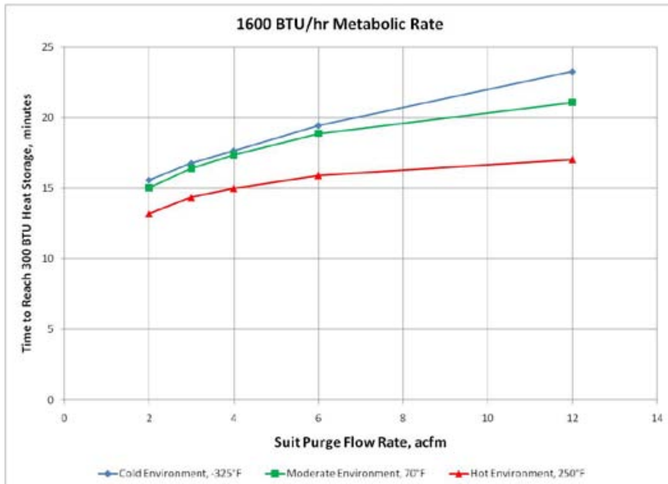


Figure 15. 1600 BTU/hr Metabolic Rate Cases

Figure 16. 2000 Metabolic Rate Cases

V. Conclusion

An analysis task was performed to determine the helmet and suit purge flow rates required to sustain a crew member during an EVA retreat/abort scenario. Helmet purge flow rates were determined by calculating the amount of CO_2 washout that would yield an inhaled CO_2 value of 20 mmHg by the simulated crew member. The CFD results from the CO_2 washout analysis and a thermal spreadsheet model were used to assess the potential problem of helmet fogging during the helmet purge activity. Suit purge flow rates were determined by calculating the required convection cooling (function of flow rate) needed for keeping a simulated crew member comfortable in the absence of water loop cooling.

The CFD helmet purge analyzed cases predicted that purge flow rates equal to 1.7, 1.5, and 1.2 acfm would be required for metabolic rates equal to 2000, 16000, and 1200 BTU/hr, respectively, in order to provide adequate CO_2 washout. Adequate CO_2 washout was defined as providing the minimum amount of flow to meet an inhaled CO_2 partial pressure of 20 mmHg.

The helmet fogging analysis predicted that helmet fogging would occur in the crew member's field of view for all of the CO_2 washout flow rates analyzed. The human respiratory water vapor production rate was based on a 100% H_2O saturation assumption for the exhaled gases which equated to a low metabolic rate (~750 BTU/hr) for the assumed breathing pattern. The analysis assumed the crew member was in a worst case cold environment, which predicted a helmet inner bubble temperature of 53°F. Increasing the inner bubble temperature to 64°F produced minor changes to the amount of fogging produced for the helmet purge flow rates analyzed. However, increasing the helmet purge flow rate to 4 acfm did significantly reduce the amount of fogging in the crew member's field of view. Linear extrapolation of the data predicted that flow rates equal to 7 and 9 acfm would be required to totally prevent fogging on a helmet bubble at temperatures of 64°F and 53°F, respectively. These required flow rates would be even higher if the assumed breathing pattern was adjusting for higher metabolic rates. The large helmet purge flow rates required to prevent fogging could be mitigated if an anti-fogging coating approach is successful.

Results for the suit purge cases analyzed showed that keeping a suited crew member comfortable for 30 minutes could not be accomplished for high metabolic rates (1600 and 2000 BTU/hr) with only convective cooling. Convective cooling with suit purge flow rates ranging from 2 to 4 acfm could not keep a simulated crew member with a moderate metabolic rate (1200 BTU/hr) comfortable for 30 minutes. Increasing the suit purge flow rate to 6 acfm showed comfort periods greater than 30 minutes for a crew member with a moderate metabolic rate in a cold and moderate thermal environment. Further increasing the suit purge flow rate to 12 acfm showed the comfort level being extended beyond 30 minutes for a crew member in a hot thermal environment experiencing the same 1200 BTU/hr metabolic rate. All of the cases that assumed an 800 BTU/hr metabolic rate gave crew comfort periods greater than 30 minutes, except for the case that assumed a 2 acfm suit purge flow rate in a hot thermal environment.

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